

SPATIAL-DEPENDENT DIFFUSION OF COSMIC RAYS AND THE RATIO OF \bar{P}/P , B/C

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ABSTRACT

Recent precise measurements of cosmic ray spectral revealed an anomalous hardening at ~ 200 GV for nuclei from PAMELA, CREAM, ATIC, AMS02 experiments and at tens of GeV for primary electron derived from AMS02 experiment. Particularly, the latest observation of \bar{p}/p ratio by AMS02 demonstrated a flat distribution, which further validated the spectrum anomalies of secondary particles. All those new phenomena indicated that the conventional propagation model of cosmic rays meet challenge. In this work, the spatial-dependent propagation coefficient $D(r, z, \rho)$ is employed by tracing the source distribution under the physical picture of two-halo model in DRAGON package. Under such scenario, the model calculation will result in a two-component spectral for primary nuclei and electron. Simultaneously, due to the smaller rigidity dependence of $D(r, z, \rho)$ in galactic disk, the ratio of secondary-to-primary will be inevitably flatter than the calculation in the conventional propagation model. As a result, we can reproduce the spectral hardening of proton, electron and the flat ratio of \bar{p}/p and B/C by only adopting the spatial-dependent propagation coefficient $D(r, z, \rho)$ in galactic disk.

1. INTRODUCTION

Great progress in Cosmic Ray (CR) spectrum measurement has been made in recent years with new generation of space borne and ground based experiments in operation. The fine structure of spectral hardening for primary nuclei at 200 GV was observed by ATIC-2 (Panov et al. 2006), CREAM (Ahn et al. 2010) and PAMELA (Adriani et al. 2011). Just recently, AMS02 also confirmed the hardening, though the spectral line-shape has a bit discrepancy with each other (Giesen et al. 2015). Several kinds of explanations have been proposed to understand the origin of the spectral hardening, including: the contribution from nearby SNRs (Thoudam & Hörandel 2012), the re-acceleration mechanism of old SNRs sources (Biermann et al. 2010), the combination effects from different group sources (Zatsepin & Sokolskaya 2006; Yuan et al. 2011) and the spatial-dependent diffusion of CRs (Tomassetti 2012; Gaggero et al. 2015a; Jin et al. 2015a).

Along with the acceleration of nuclei, the primary electron can also be accelerated to high energy. This hints that the spectral hardening should happen in the primary electron. To reconcile the AMS02 positron fraction and total e^\pm spectral observed by Fermi-LAT/HESS, the hardening spectral for primary electron was predicted by the work (Yuan & Bi 2013; Yuan et al. 2015). Soon after the AMS02 publication of the e^\pm spectral (Aguilar et al. 2014), the primary electron flux was derived from the subtraction of positron flux as $\Delta\phi = \Phi_{e^-} - \Phi_{e^+}$ (Li et al. 2014). The most interesting thing was that the spectrum index shows roughly constant character (Li et al. 2014) above tens of GeV, which was conflictive with the softening variation with energy in the Conventional Propagation Model (CPM) (Li et al. 2014; Lin et al. 2014). After subtracting the flux from the calculation in CPM, the excess was uncased with the peak energy at ~ 100 GeV (Li et al. 2014). In one words, more and more studies accepted the spectrum hardening for the primary electron

with recent high precise measurement at high energy. The possible twinborn origin with nuclei has been proposed from the spatial-dependent propagation under the physical schema of Two-Halo-Model (THM) (Tomassetti 2012) in our previous work (Jin et al. 2015a).

Similar phenomena also happened in the secondary particles. The ratio of \bar{p}/p and B/C are tagged to be the characteristic quantity to calibrate the propagation of CRs. The predicted $\sim E^{-\delta}$ for secondary-to-primary lead to a sharp softening with energy for the ratio of \bar{p}/p and B/C in the CPM. Considering the uncertainty, the previous result of \bar{p}/p from PAMELA experiment seemed to be compatible with the CPM at the energy range of GeV to tens of GeV (Adriani et al. 2014a, 2010). Thanks to AMS02 experiment, the ratios of \bar{p}/p and B/C are measured from GeV energy to hundreds of GeV with high precision (Giesen et al. 2015). It is very exciting that the ratio of \bar{p}/p is almost flat from ~ 10 GeV to hundreds of GeV, which obviously challenge the CPM. This new result has stimulated several theoretical studies with point of view from either exotic physics (Lin et al. 2015; Chen et al. 2015b; Geng et al. 2015; Huo et al. 2015; Ibe et al. 2015; Cheung & Sanford 2015; Chen et al. 2015a; Hamaguchi et al. 2015; Jin et al. 2015b) and some authors proposed that the slower diffusion in high energy can also result in the \bar{p} excess (Giesen et al. 2015; Cowsik & Madziwa-Nussinov 2015; Kappl et al. 2015).

With all of these high precision measurements in hand, one should ask whether a unified physical mechanism can result in those anomalous phenomena. A phenomenological model has been proposed to explain those anomalies by adopting the Hard Galactic Plane Component (HGPC) and predicted the flat distribution of \bar{p}/p , which was highly consistent with the later observation of AMS02 (Guo et al. 2014). One possible mechanism of the HGPC is the smaller rigidity dependence of diffusion in the galactic plane, such as THM. Inspired by this work, The optimal bedrock is from the understanding of CPM and compensate the missing parts in the CPM.

The diffusive properties were assumed to be the same and this hypothesis leads to a uniform spectrum index for primary particles and their production of secondary ones in the whole galaxy in the CPM. A natural solution is to consider the spatial-independent propagation. One ready example is the THM, proposed by Tomassetti (Tomassetti 2012), where the the propagation volume was divided into two regions as Inner Halo (IH) and Outer Halo (OH). The key point of THM is that the diffusion coefficient has a smaller rigidity dependence in the thin IH than in the wide OH, which can result in the a two-component spectrum. In 1 D analytical calculation, the spectrum hardening of nuclei spectra at rigidity of ~ 200 GV, observed by ATIC-2 (Panov et al. 2006), CREAM (Ahn et al. 2010) and PAMELA (Adriani et al. 2011), were successfully reproduced (Tomassetti 2012). Following this picture, Jin et al. extend it to 2D space and explain the spectrum hardening of primary electron (Jin et al. 2015a). The THM can work well in explanation of the spectral hardening of the primary CRs. It is necessary to continue further study to examine the secondary production of the new observation of \bar{p}/p and B/C .

The IH, actually called disk, contain almost all the galactic astrophysical object, which can generate large irregularities of the turbulence and play important impact to the diffusion properties. This imply that the diffusion coefficients is possibly related to the source distribution. On the contrary, the OH has scarce active sources and the dominant contribution of turbulence come from the CRs themselves (Tomassetti 2012). This means that the diffusion coefficients can be fixed to constant. Such physical schema was consistent with the diffuse γ -ray observation by Fermi-LAT (Ackermann et al. 2012), which shows that the excess over the prediction of CPM is only existed in the galactic plane. Furthermore, the observed power-law index ranges from $E_\gamma^{-2.47}$ to $E_\gamma^{-2.6}$, resulting in a more harder spectrum in more close to the GC (Gaggero et al. 2015b). The spatial diffusion coefficients should also depend on the radial coordinate. This paper tend to reproduce the spectrum hardening of primary particles and simultaneously reproduce the ratios of \bar{p}/p , B/C by introducing the spatial-dependent diffusion parameters, which derived by tracing the source distribution.

The paper is organized in the following way. Section 2 describes the spatial-dependent propagation of CRs, Section 3 presents the results of the calculation compared with the observation. Finally, Section 4 gives the conclusion.

2. SPATIAL-DEPENDENT PROPAGATION OF CRS

During the active phase of astrophysical object such as SNRs (Bell 1978a,b; Blandford & Ostriker 1978), Galactic Center (Ptuskin & Khazan 1981; Said et al. 1981; Giler 1983; Guo et al. 2013) and other ones, the expanding diffusive shocks are generated and can accelerate the CRs to very high energy. Before arriving at earth, those CRs have traveled in the galaxy for $\sim 10^7$ years after they diffuse away from the acceleration site (Garcia-Munoz et al. 1977). During the journey, the impacts due to the fragmentation and radioactive decay in the ISM result in the production of secondary particles.

Meanwhile, the electron suffers energy loss in the interstellar radiation field (ISRF) and magnetic field. The story to experience in the long journey can be described by the propagation equation as:

$$\begin{aligned} \frac{\partial \psi(\vec{r}, p, t)}{\partial t} = & q(\vec{r}, p, t) + \vec{\nabla} \cdot (D_{xx} \vec{\nabla} \psi - \vec{V}_c \psi) \\ & + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi - \frac{\partial}{\partial p} \left[\dot{p} \psi - \frac{p}{3} (\vec{\nabla} \cdot \vec{V}_c \psi) \right] \\ & - \frac{\psi}{\tau_f} - \frac{\psi}{\tau_r} \end{aligned} \quad (1)$$

where $\psi(\vec{r}, p, t)$ is the density of CR particles per unit momentum p at position \vec{r} ; \vec{V}_c is the convection velocity; τ_f and τ_r are the characteristic time scales for fragmentation and radioactive decay respectively; $q(\vec{r}, p, t)$ is the source distribution; D_{xx} and D_{pp} are the diffusion coefficients in coordinate and momentum space respectively. In this formula, three stages of the evolution for observed CRs are also sketched out as: injection, propagation and solar modulation.

Injection Spectral: Though many kinds of astrophysical objects can accelerate the CRs to very high energy, SNRs have long been considered as the dominant candidates of GCRs. The accelerated spectrum of primary CRs at source region is assumed to be a broken power law function and the formula is similar as precious works (Guo et al. 2014; Jin et al. 2015a). At high energy, the exponent cut-off at ~ 4 PeV is adopted for nuclei and a broken power law at \sim TV with power law index -4.1 is selected to agree with HESS and VERITAS observation (Aharonian et al. 2008; Staszak & for the VERITAS Collaboration 2015). Detailed information of the parameters is listed in Table 1.

TABLE 1
THE INJECT SPECTRUM OF PRIMARY CRs

parameters	Nuclei	Electron
$\log(q_0^b)$	-8.31	-9.367
ν_1	1.9	1.86
ν_2	2.39	2.76
$p_{br}(GV)$	9.5	4.2

Propagation Coefficients: The spatial diffusion coefficient was a power law form as $D_{xx} = D_0 \beta (\rho/\rho_0)^\delta$, where ρ is the rigidity and δ reflects the property of the ISM turbulence. The re-acceleration can be described by the diffusion in momentum space and the momentum diffusion coefficient D_{pp} is coupled with the spatial diffusion coefficient D_{xx} as (Seo & Ptuskin 1994)

$$D_{pp} D_{xx} = \frac{4p^2 v_A^2}{3\delta(4-\delta^2)(4-\delta)w} \quad (2)$$

here v_A is the Alfvén speed, w is the ratio of magnetohydrodynamic wave energy density to the magnetic field energy density, which can be fixed to 1. The CRs propagate in an extended halo with a characteristic height z_h , beyond which free escape of CRs is assumed.

Based on the discussion about the THM in introduction, the spatial-dependent diffusion coefficients can be described as:

$$D(r, z, \rho) = \begin{cases} D'_0(r, z) \beta(\frac{\rho}{\rho_0})^{\delta(r, z, \rho)} & |z| < \xi z_h \text{ (IH)} \\ D_0 \beta(\frac{\rho}{\rho_0})^{\delta_0} & |z| > \xi z_h \text{ (OH)} \end{cases} \quad (3)$$

where ξ is the fraction of the half thickness of IH to the halo height z_h . The diffusion coefficients is dependent on the irregular turbulence, which possibly arises from the violent activity of astrophysical object, such as SNRs, pulsars, stellar winds, OB stars and so on (Erlykin & Wolfendale 2013). That is to say that the diffusion coefficients can be derived by the source distribution.

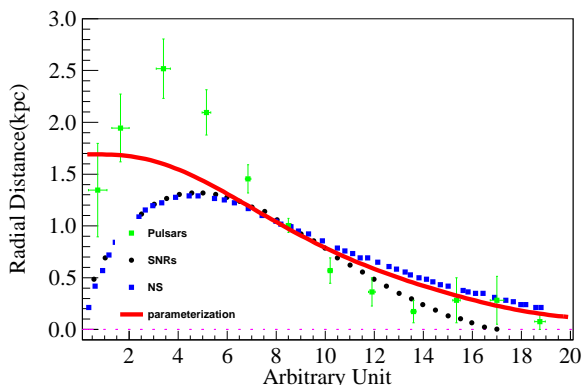


FIG. 1.— Radial distribution of astrophysical objects: Pulsar, SNRs and NS (Yusifov & Küçük 2004). The red line is the "scale-line", derived from the combined source distribution and extended to the GC.

Fig. 1 shows the radial distribution of astrophysical object: pulsar, SNRs and NS (Yusifov & Küçük 2004). Though the radial distribution become slow down toward GC, the irregularity of turbulence and magnetic-field is more larger in more near the GC region. Evidences that there is an increase in turbulence as one approaches the GC are provided by observations of magnetic field (Beck 2009) and thermal bremsstrahlung (Planck Collaboration et al. 2011). Combined with the source distribution and the magnetic field information toward GC, the irregularity turbulence along radius can be built as the red solid line, here we call it "scale-line". It is true that the shape of scale-line is a bit subjective. However, the scale-line is only served to describe the radial dependent diffusion property, which can be determined by the spectral observations as following discussion. Furthermore, the galactic source is very sparse and can be neglectful in OH. The dominant contribution of turbulence come from the CRs themselves (Tomassetti 2012) and the diffusion coefficients can be dealt with constant reasonably. The diffusion coefficients of $D'_0(r, z)$ and $\delta(r, z)$ can be described in a unified formula as:

$$F(r, z) = \begin{cases} (A/(1 + \exp(f(r))) - B)(z/\xi z_t)^n & \text{(IH)} \\ C & \text{(OH)} \end{cases} \quad (4)$$

where $f(r)$ is the scale-line; the factor $(z/\xi z_t)^n$ is used to describe the smooth connection between two halos and can be fixed to 4 (similar with the work (Jin et al. 2015a)); A, B, C are free parameters, which can be fixed by fitting the observation spectral. Formula 4 seems a

little complicated. Actually, we can also select the simplest format $\delta(r) = A \bullet r + B$, but need to deal with the region close and far ($r > 11$ kpc) from GC to avoid the saturation as the work (Gaggero et al. 2015b). Here we just intend to get a quantitative and smooth diffusion coefficient along the radial coordinate and adopt the formula 4. By adopting the values of the parameters as showing in Table 2, Fig. 2 shows the radial and Z-direction distribution for D' and δ respectively.

TABLE 2
THE PARAMETERS OF SPATIAL-DEPENDENT DIFFUSION.

parameters	$D'(r, z)$	$\delta(r, z)$
A	1.5	1.35
B	0.12	-0.19
C	0.9	0.46
ξ	0.16	\sim

Solar Modulation: When the low energy CRs arrive at the solar environment, the direction of motion will be affected by the solar wind, which are called solar modulation. The force-field approximation is used to describe the solar modulation by the modulation potential Φ (Gleeson & Axford 1968). In this work, The modulation potential Φ is fixed as $\Phi=500$ MV for proton, \bar{p} , lepton and $\Phi=200$ MV for B/C.

3. CALCULATION RESULTS

In this calculation, we employ the publicly available numerical code DRAGON, which was designed to solve the spatial-dependent propagation of CRs (Evoli et al. 2008). By adopting one set of diffusion coefficient as discussed in above, we perform the calculation of primary spectral for proton, electron and the ratio of secondary-to-primary for \bar{p}/p , B/C.

3.1. The Spectral of primary proton and electron

The left panel of Fig.3 shows the spectrum comparison between model calculation and the experimental results for proton. The solid blue line represents the model calculation. The spectrum break is clearly reproduced starting from hundreds of GeV, which are consistent with the observation from AMS02 experiment, but a little lower than the observations of PAMELA and ATIC at TeV energy range. According to above discussion, the break position and amplitude of spectrum is dependent on the fraction ξ and δ in the inner halo. High precise measurement in TeV energy range is expected to determine those parameters in future.

The left panel of Fig.3 shows the spectrum comparison for primary electron. The flux of primary electron was derived from the subtraction of positron flux as $\Delta\phi = \Phi_{e^-} - \Phi_{e^+}$ (Li et al. 2014) base on the AMS02 observation of e^\pm (Aguilar et al. 2014). It is obvious that the spectrum break is reproduced starting from tens of GeV and well consistent with the data.

3.2. The ratio of \bar{p}/p and B/C

The left panel of Fig.4 shows the calculated \bar{p}/p and the right panel shows the B/C. The blue lines present the calculated results from the spatial-dependent propagation. The ratio of \bar{p} is raised up at high energy and

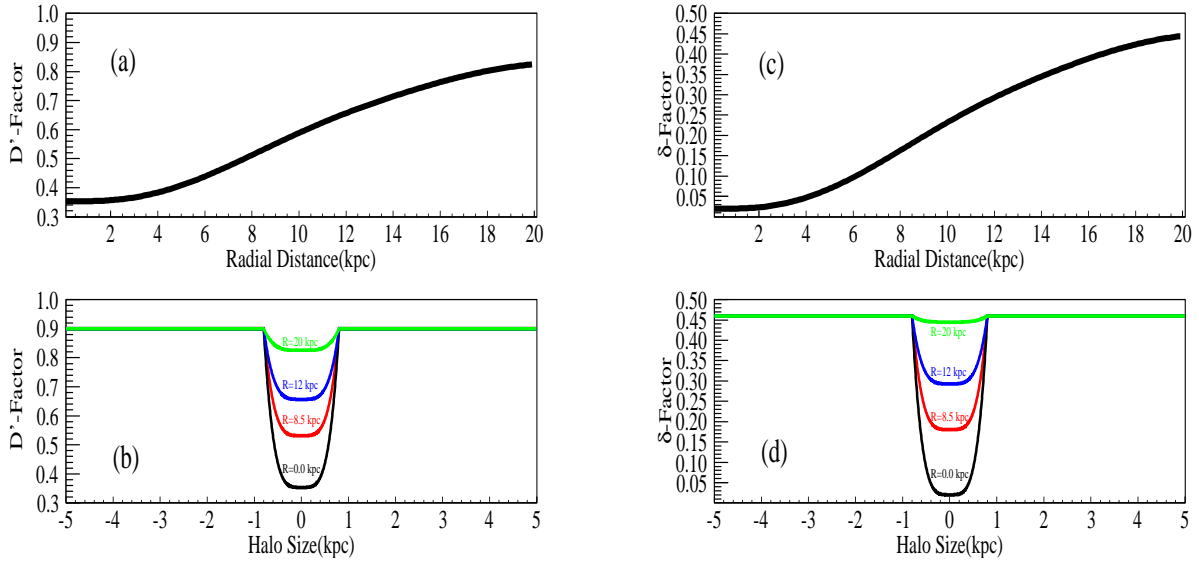


FIG. 2.— The distribution of spatial-dependent diffusion coefficient: $D(r,z)$ and $\delta(r,z)$ in radial and z direction, here (a) is the D' -Factor along radial coordinate; (b) is D' -Factor along Z coordinate at different radius; (c) is δ -Factor along radial coordinate and (d) is δ -Factor along Z coordinate at different radius.

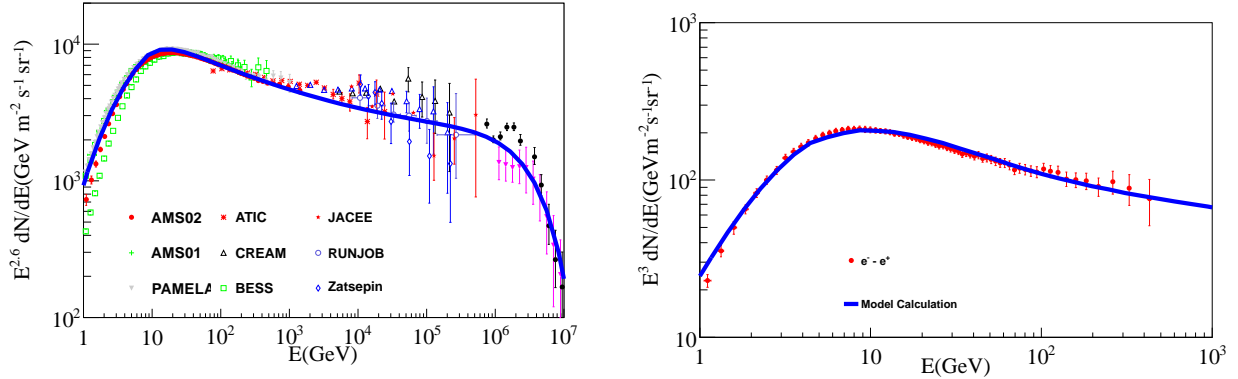


FIG. 3.— The comparison between model calculations and observations for primary spectral of proton and electron. The experiment data of proton come from: AMS02(Giesen et al. 2015), ATIC(Panov et al. 2006), PAMELA(Adriani et al. 2011), AMS01(Alcaraz et al. 2000), CREAM(Ahn et al. 2010), BESS(Sanuki et al. 2000), JACEE(Asakimori et al. 1998), RUNJOB(Apanasenko et al. 2001), KASCADE(Antoni et al. 2005). The e^+e^- data come from (Aguilar et al. 2014).

consistent with the measurement of AMS02 within errors. Below ~ 2 GeV energy, the model calculation is consistent with PAMELA and a little lower than the measurement of AMS02. However, the uncertainty of \bar{p} production cross section is $\sim 25\%$ in the energy range 0.1 - 100 GeV (Donato et al. 2001, 2009), which should lead to a same level of uncertainty in the ratio calculation. Taking all of those factors into account, the model calculation is consistent with the observation within the errors. On the other hand, the ratio of B/C is quite consistent with AMS02 observation, except a little higher at ~ 1 GeV.

Anyway, Owing to its hard spectrum component at inner halo, the CRs induced secondary \bar{p} and Boron inherit a similar hard spectrum, which make the ratio of $\bar{p}/p, B/C$ considerably flatter than that from conventional model. Such a tendency is favoured in just recent \bar{p}/p observation by AMS02 below TeV energy region. In the future, high statistic and TeV energy observation can offer a crucial and definitive identification of this model.

4. CONCLUSION AND FUTURE WORK

In this work, the spatial-dependent propagation parameter are derived from the source distribution under the THM scenario. By adopting one set of parameters, the primary spectral hardening of proton and electron are reproduced following previous work (Tomassetti 2012; Jin et al. 2015a). Simultaneously, the new observed \bar{p}/p and B/C ratios can be reproduced under this model. High statistic and TeV energy observation can offer a crucial and definitive identification of this model in future.

Currently, we only carry out the calculation of charged CRs and comparison with observations in solar system. The γ -ray emission can be used as a direct probe of the CR intensities and spectra in distant location which can serve to determine the spatial-dependent diffusion coefficients. Actually, our parameter of $\delta(r)$ reflects this property as discussed in the work (Erlykin & Wolfendale 2013; Gaggero et al. 2015b). Further studies about the γ -ray emission can be performed in our future work.

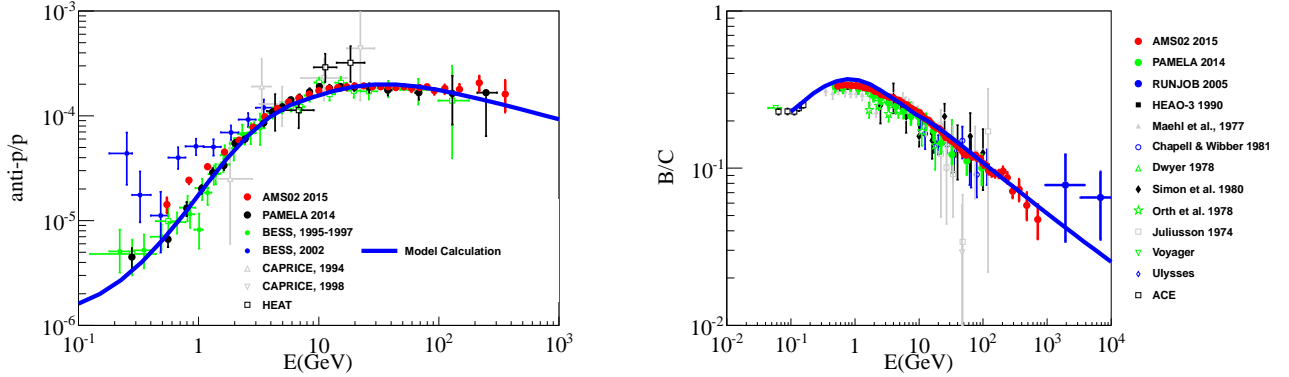


FIG. 4.— The calculated \bar{p}/p (left panel) and B/C (right panel). The \bar{p}/p data from: AMS02 2015 (Giesen et al. 2015), PAMELA 2014 (Adriani et al. 2014a), PAMELA 2010 (Adriani et al. 2010), BESS 1995-1997 (Orito et al. 2000), BESS 1999 (Asaoka et al. 2002), CAPRICE 1994 (Boezio et al. 1997), CAPRICE 1998 (Boezio et al. 2001), HEAT (Beach et al. 2001). The B/C data from: AMS02 (Aguilar 2013), PAMELA (Adriani et al. 2014b), RUNJOB (Derbina et al. 2005), Juliusson (Juliusson 1974), Dwyer (Dwyer 1978), Orth (Orth et al. 1978), Simon (Simon et al. 1980), HEAO-3 (Engelmann et al. 1990), Maehl (Maehl et al. 1977), Voyager (Lukasiak 1999), Ulysses (Duvernois et al. 1996), ACE (Davis et al. 2000) and for other references see (Stephens & Streitmatter 1998).

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Note added: While this paper was in preparation, one similar papers on interpretation for the spectral hardening under the two-halo model scenario appeared (Tomassetti 2015).

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